Utilisation of coal bottom ash for the production of compressed building blocks in Sub-Saharan countries

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Abstract

Coal provides 30% of global primary energy needs and generates over 41% of the world's electricity. Total world coal production reached a level of 8022.5 Mt in 2014 [1]. Coal Combustion Residues (CCRs), also known as Coal Combustion Products, are wastes from thermal power stations. These include fly ash (FA), bottom ash (BA), boiler slag, fluidised bed combustion ash, flue gas desulfurization. Valorisation of FA is very common, particularly in the cement industry [2], but BA utilisation is often limited to low added value applications like concrete aggregates [3], low cost embankment/filling material or blasting grit/roofing granules [4]. Reuse may include lightweight embankment for rockfall protection. In Sub-Saharan countries, reuse of coal combustion waste is still underexploited.

This paper describes some results from an experimental investigation aimed at the development of unfired compressed block with coal bottom ash from Niger. Physical and microstructural characterisation of BA, as well as environmental profile assessment, were carried out. Several blends of BA, lateritic clayey soil and Portland cement were tested for the production of compressed blocks with a hand-operated press, obtaining compressive strengths ranging from 4 to 27 MPa. Obtained blocks showed good mechanical strength and low weight with a Portland cement content as low as 20%. Compressive strength up to 600 °C in furnace gave satisfactory results.

1. Introduction

Despite a general reduction trend in the developed Countries in favour of renewable energies, coal still provides 30% of global primary energy needs and generates over 41% of the world's electricity [1]. Production and use of coal play an important role in the energy mixes of many Asian countries, as well as in some Eastern Europe countries and in traditionally coal-rich countries such as South Africa. Coal Combustion Products (CCPs) are wastes from thermal power stations, such as fly ash, bottom ash, boiler slag, fluidised bed combustion ash, flue gas desulfurization. A summary of the most recent data available on CCP production and utilisation is give in Table 1.

Table 1 Production and utilisation of CCPs in major producer Countries

Country	CCPs Production (Mt)	Utilization Rate	Year	Reference
USA	106	52%	2015	[4]
China	~350	58%	2010	[5]
India	258*	n.a.	2014	[6]
EU15	48	88%	2010	[7]
Australia	12	40%	2015	[8]
Canada	6	28%	2011 - 2013	[9]
Africa	31	10%	2010	[10]

* calculated according to a declared 40% ash content

According to a report of the International Energy Agency, Africa has some 120 billion tonnes of coal resources, most of these concentrated in the southern part of the continent. South Africa, Mozambique, Zimbabwe, Botswana, Tanzania, Zambia, Swaziland and Malawi are endowed with significant coal reserves [11]. The Niger Coal Society (*SONICHAR, Société Nigérienne de Charbon*) has been created in 1975 in order to reduce the foreign energy demand of Niger supplying energy to the mining societies established in Arlit and in Akokan, as well as to the towns of Agadez and Tchirozérine. The power station coal-fuelled is equipped by two 18.8 MW generators and produces about 150,000 tons of CCPs yearly. The coal combustion is obtained with a Ignifluid type furnace patented by Fives Cail Babcock in mid-'80, consisting on a fluidised bed furnace-type incorporating a mobile grid that drags the crushed coal upwards and directly discharges combustion residues (Bottom Ash – BA) in a temporary stocking area (see Figure 1). The coal is locally mined at the site of Tefereyre, 75 km north-west to Agadez.

Figure 1. BA stocking area.

In order to find a possible utilisation for the large amount of BA produced by the power station, the company Sonichar and the International Institute for Water and Environmental Engineering (Burkina Faso) carried out a research program focused on the assessment of physical and chemical properties of BA, aiming at the development of suitable mix proportions for the production of compressed building blocks.

2. Materials and Methods

Samples of BA were obtained by Sonichar plant and were tested for physical characterisation. Grain size distribution resulted in a sandy gravel, with D_{50} about 4 mm. Specific gravity was measured in the range of 2.2, whereas bulk density was in the range 0.7 – 0.9 t/m^3. A very high porosity, in the range 65 – 70% was measured, which presumably resulted from the combined effects of macro-porosity (inter-grain porosity) and micro-porosity (grain structure).

EDAX analysis on the BA indicated that alumino-silicates accounted for 85% – 90% of the material, with Si in the range 55% - 65% and Al in the range 20 – 35%. X-Ray diffraction coupled with Rietveld analysis (carried out with corundum as internal standard) showed that the amorphous phases represent about 61% of the sample, whereas mullite ($Al_{4,56}Si_{1,44}O_{9,72}$) and quartz ($SiO_2$) were the main crystal structures observed, representing around 22% and 11% respectively. It is to be supposed that alumino-silicates might be largely present in its amorphous phase, as well as K and Mg. Hematite Fe_2O_3 and Rutile TiO_2 were found as minor crystal components (<1%). A Scanning Electron Microscopy (SEM) image of the BA is shown in Figure 2, where the glassy structure of the material can be appreciated.

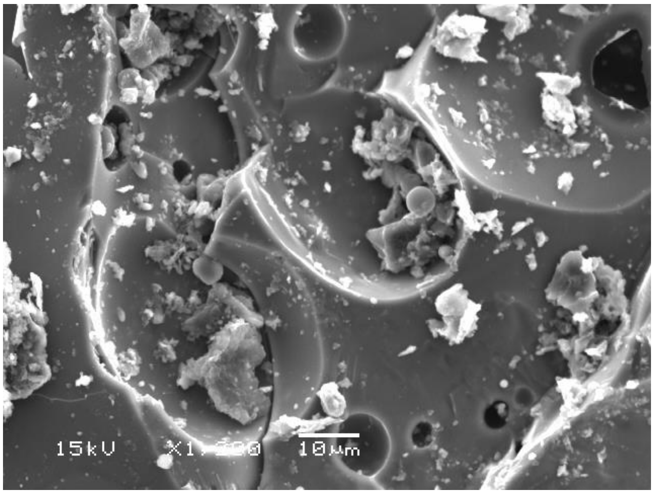

Figure 2. SEM image of BA.

Leaching tests were carried out in order to assess potential pollution hazards, using demineralised water as leaching medium with a liquid/solid ratio equal to 10. The mix was magnetically stirred for 24 hours, then filtered on a 0.45 μm membrane. A spectrophotometer has been utilised for the detection of Na, K, whereas an atomic spectrophotometer with flame atomisers has been used for Ni, Pb, Cr, Cd and Cu respectively. Traces of Cd (0.20 ppm) and Cu (0.10 ppm) were detected along with alkali metals such as Na and K.

A 100 L pan-type (Figure 3, left), vertical shaft mixer was used for blending the dry materials, adding subsequently the water up to the reach of a suitable plasticity of the mix. Bricks were produced via a Testaram hand-operated press (Figure 3, right), applying an average force of 150 kN (as per press producer datasheet). About 20 to 30 bricks sized 14 cm x 14 cm x 9 cm were moulded for each mix. During the first 7 days of curing, bricks were moistened through water spraying and covered by a black plastic sheet.

Figure 3. (Left) vertical shaft mixer. (Right) hand operated Testaram press.

Preliminary tests using neat BA for the production of compressed building blocks were not successful due to the lack of plasticity of the raw material and a lack of binding. Portland CEM I 42.5 cement powder, lateritic soil (Liquid limit LL=50, Plasticity Index PP=22, clay content about 40%) and uniform siliceous sand were used as stabilising agents in several combinations. A total number of 12 diverse formulations was tested, with mix compositions as per table 2.

Brick compressive strength was tested at 7, 21, 28 and 45 days of curing. According to Rilem standard for compressed earth block test [12], two coupled bricks were crushed at each test, greasing surfaces between samples and press for reducing the contact friction. Sample dimensions were measured with electronic callipers (resolution 0.01 mm and full scale 200 mm), and sample were weighted with an electronic scale (resolution 0.1 g and full scale 6000 g). Compressive strength was tested with a 1500 kN hydraulic press, equipped with a pressure cell (400 bar full scale) and a LVDT transducer (65 mm full scale). Data gathered via a data logger driven by a LabVIEW routine. About 300 bricks were produced. Tests on each brick parameter combination (mix dosage, curing time) were carried out in triplets.

3. Results and discussion

Compressive strength of moulded bricks increases with curing time and with cement ratio (see Figure 4). Strength values were consistent with literature UCS for cement-stabilized earth unfired bricks [13]. Neat cement stabilisation results showed that compressive strength increased linearly with the cement ratio. Compressive strength higher than 5 MPa was observed for 20% and 30% cement inclusion after only 7 days of curing, whereas this value was not reached for the 10% ratio after 45 days of curing. At 28 days, 20% and 30% mixes resulted in a strength of 10 MPa, and their final strength was about 11 MPa and 13 MPa respectively. 57% ratio was tested as 1:1 ratio and gave the best results: 14 MPa after 7 days, almost 22 MPa after 45 days, 27 MPa as final strength.

Table 2 Composition of mixes with BA, cement, laterite and sand

Sample label	M10	M20	M30	M57
Cement ratio	10%	20%	30%	57%
BA volume (l)	75	75	75	75
Cement volume (l)	7.5	15	22.5	42.75
Water volume (l)	6	7.5	5.5	8.5
Final moisture content	25%	24%	22%	24%
Sample label	**ML(10+20)**	**ML(10+30)**	**ML(20+20)**	**ML(20+30)**
Cement ratio	10%	10%	20%	20%
Laterite ratio	20%	30%	20%	30%
BA volume (l)	60	52.5	60	52.5
Cement volume (l)	7.5	7.5	15	15
Laterite volume (l)	15	22.5	15	22.5
Water volume (l)	5.5	6	6	7
Final moisture content	24%	24%	22%	28%
Sample label	**MS(10+20)**	**MS(10+30)**	**MS(20+20)**	**MS(20+30)**
Cement ratio	10%	10%	20%	20%
Sand ratio	20%	30%	20%	30%
BA volume (l)	60	52.5	60	52.5
Cement volume (l)	7.5	7.5	15	15
Sand volume (l)	15	22,5	15	22,5
Water volume (l)	4.5	4	5	5
Final moisture content	23%	19%	19%	17%

As far as cement – sand stabilisation is concerned, no effect was observed by varying the sand ratio in the mix, as the compressive strength seemed driven uniquely by the cement dosage. It was therefore concluded that sand addition was not effective in increasing the brick strength.

Cement + laterite stabilisation proved to be the most effective treatment. When cement was added at 10%, almost no difference has been observed between the compressive strength of neat cement (M samples) and cement + sand (MS samples), whereas cement + laterite (ML samples) showed a strength increment between 50% and 75%. With cement dosage equal to 20% a similar pattern was observed, with strength increment less pronounced. It was also observed that compressive strength of samples with lateritic soil dosage equal to 20% was higher than samples with lateritic soil dosage equal to 30% irrespective of the cement dosage.

Brick unit weight decreases over curing time. Unit weight of moulded bricks was found to be lower than other building materials, ranging from 1.2 to 1.6 g/cm^3 after 45 days of curing. This property, due to the very high porosity of the utilized BA, is a clear advantage for brick utilisation in lightweight works as well as in thermal insulation applications. The relationship between compressive strength and unit weight followed two trends: (a) a reduction due to the drying of the sample; (b) an increase due to the mix composition (i.e. the cement addition rate).

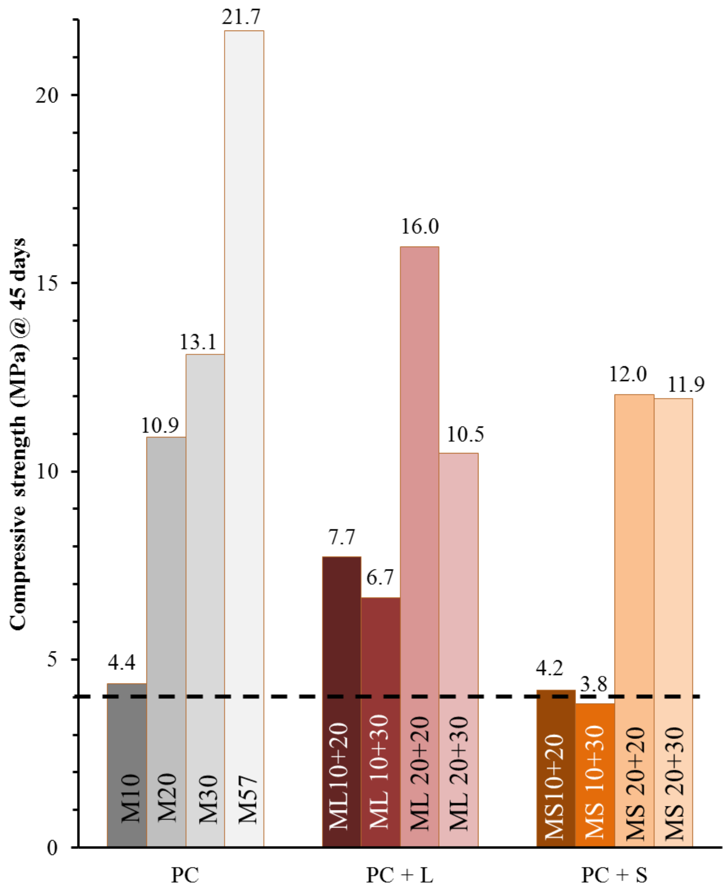

Figure 4. Compressive strength results at 45 days. Dashed line: 4 MPa target strength.

The strength development of cement-stabilised bricks was compared with existing theoretical models for concrete and it was observed that strength increased even after the typical curing period. Two theoretical models from the French technical recommendations BAEL 91 were compared with results for M30 and M57, for which data up to 140 days were available. Results are shown in Figure 5. Though the two models were consistent with experimental results until d = 45 days, BAEL 91 model did not give a correct prediction over longer time, underestimating final strength. The second formulation gave a better representation of strength development for M57, but seemed to underestimate data from M30 series. The steady increment in strength can be due to some pozzolanic reactions in the samples, or to the partial dissolution and reorganisation of silicoaluminate compounds (i.e. "geopolymeric" reaction) due to the presence of an alkaline activator, hydrated lime from Portland cement in this case.

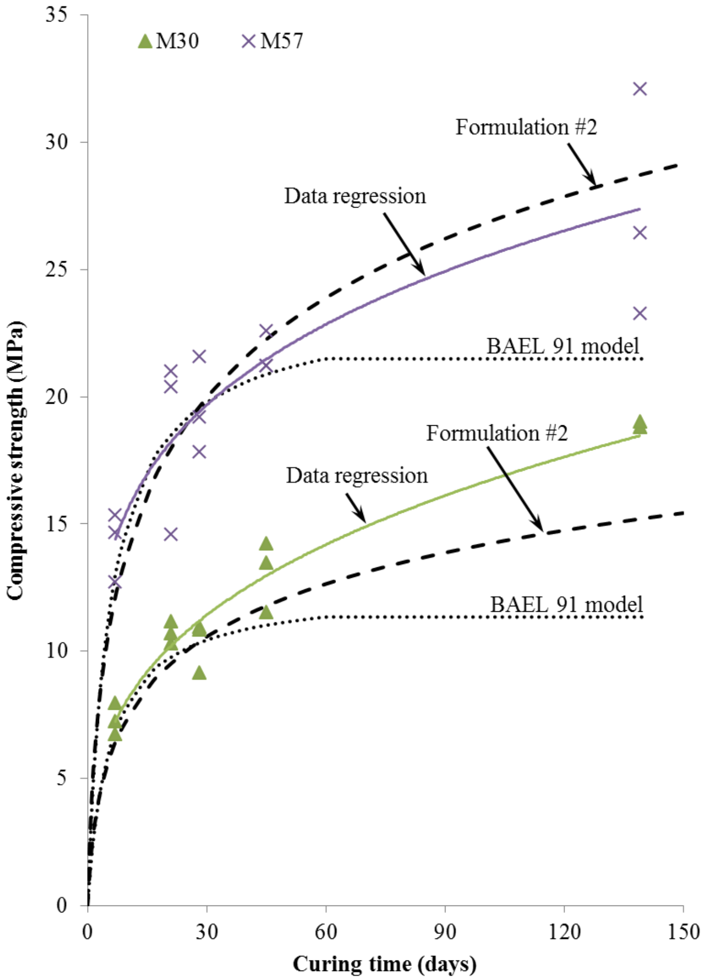

Figure 5. Compressive strength development.

Cement + laterite blocks were tested for assessing their thermal stability. Tests were carried out by heating samples in a furnace at 200 °C, 400 °C and 600 °C, with a heating rate of 0.5 °C/min, keeping the test temperature for 1 hour and then cooling the samples at the rate of 0.5 °C/min. Mass losses between 3% and 10% for 200 °C and 600 °C were recorded, with 60% of the mass loss occurring after 400 °C and associated with the dehydration of clay minerals. Compressive strength was found to increase from room temperature to 200 °C, then a reduction was observed at 400 °C (although 15% higher than the initial strength), whereas at 600 °C the strength was about 40% lower than the initial value. Literature values indicate a reduction of 55% at 600 °C for typical concrete. From 400 °C to 600 °C brick colour faded from grey to red, due to the goethite (iron hydroxide) dehydroxilation in iron oxide.

Figure 6. Brick appearance after furnace heating.

4. Conclusions

A low-cost and "low-tech" valorisation strategy for coal combustion residues in developing Countries was proposed. Results showed that BA can be used with 10% cement powder and 20% clayey soil for the production unfired bricks with 8 MPa compressive strength. Higher strength can be obtained by increasing the cement ratio, whereas mixes with higher laterite ratio or with cohesionless soil like uniform sand do not perform at best. Thermal stability up to 600 °C was tested and results were promising, indicating a strength loss lower than the one typically observed for concrete.

Physical and chemical properties of BA and compressive strength development over the time, exceeding typical Portland cement behaviour, seemed to suggest potential reaction of the aluminosilicate components in alkaline environment, indicating a further possible valorisation strategy for BA as precursor material for geopolymer-based binders.

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